

Estimates of Vertex Tagging Efficiencies at a Muon Collider Higgs Factory

Bruce J. King

*Brookhaven National Laboratory
email: bking@bnl.gov*

Abstract. Tagging efficiencies and purities are estimated for the decay modes $H \rightarrow b\bar{b}$, $H \rightarrow \tau\bar{\tau}$ and $H \rightarrow c\bar{c}$ of Higgs bosons produced at an s-channel muon collider Higgs factory.

INTRODUCTION

Measurement of the branching ratios (BR) of the Higgs boson would be an important goal of a future s-channel muon collider Higgs factory. This paper derives quick, heuristic estimates of the expected tagging efficiencies and purities for the 3 main decay modes of a light, Standard Model Higgs: $H \rightarrow b\bar{b}$, $H \rightarrow \tau\bar{\tau}$ and $H \rightarrow c\bar{c}$. These estimates should be useful as input to theoretical assessments of the physics capabilities of Higgs factory muon colliders.

The vertex tagging methods are similar for $b\bar{b}$ events and $c\bar{c}$ events and these two modes are treated together in the next section. The $\tau\bar{\tau}$ mode is then discussed in a separate section, before ending with a short conclusion section.

I CHARM AND BEAUTY TAGGING

A Tagging Signatures

Higgs decays to c or b quark-antiquark pairs produce back-to-back 2-jet events with a displaced vertex in each jet from the decay of the c or b hadron.

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The goal of a vertex tagging algorithm is to find the displaced vertices and also to distinguish the $b\bar{b}$ events from $c\bar{c}$ events. The figures of merit for the tagging algorithm are the overall tagging efficiency for each of the 2 event types and the rejection factor against the other, wrong event type. In principle, one should also consider the rejection factor for hadronic events that are neither $b\bar{b}$ nor $c\bar{c}$ but, in practice, this is a much simpler task than distinguishing the 2 types with displaced vertices.

For b jets, the charged tracks in the displaced vertex will have an invariant mass up to the mass of b hadrons – about 5 GeV. There will usually be several tracks. B hadrons almost always decay into a charm hadron plus additional hadrons, so some of the charged tracks will likely form a tertiary vertex downstream from the B decay vertex. If a “topological vertexing” algorithm such as ZVTOP [1] is used then this tertiary vertex may be reconstructed. The characteristic displacement length of the vertex is $\beta\gamma.c\tau$, where $c\tau$ is 450 microns. $\beta\gamma$ would typically be about 7 for a 100 GeV Higgs decay at rest – corresponding to about 70% of the quark energy or 35% of the Higgs mass, as is seen in Z decays to b quarks – so the characteristic displacement length is about 3 mm.

The displaced vertices from charm typically have a lower multiplicity and, more significantly, a lower invariant mass than B decays since the mass of all weakly decaying charm hadrons is less than 2 GeV. In analogy to Z decays, the charm hadrons should typically carry about 50% of the c quark energy. Combining this with $c\tau = 317$ (124) microns for charged (neutral) D mesons gives characteristic decay lengths of 4 mm (1.7 mm). The lower multiplicity and lower invariant mass of charm decays makes them more difficult to tag than B decays, even for the longer lived charged D mesons.

B Jet Tagging Efficiencies

An estimate for jet tagging efficiencies and purities was made based on studies done for the proposed DESY 500 GeV center-of-mass electron-positron linear and presented in the Conceptual Design Report (CDR) [2]. This study was performed for the following scenario:

1. a 3 layer barrel vertex detector with its innermost layer a cylinder at either 1.0 cm or 2.2 cm from the interaction point (ip)
2. pixel tracking elements. Studies were performed for both charge coupled devices (CCD's) and active pixel sensors (APS's)
3. a 50–50 mix of b and c jets
4. vertex reconstruction using the SLD topological vertexing algorithm ZV-TOP [1]
5. the central region of the detector was considered.

A muon collider Higgs factory will have worse backgrounds than a linear electron-positron collider and two adjustments were made to allow for this. Firstly, APS's were assumed to be the tracking technology because CCD's are presumably too susceptible to radiation damage for use in the muon collider tracking environment and, secondly, the radius of the innermost tracking layer was assumed to be 5 cm, consistent with background studies for muon colliders [3]. This requires an extrapolation of the DESY studies.

With these adjustments, it is assumed that the Higgs factory jet tagging performance can be estimated using the DESY studies. This implicitly assumes that 2 further differences are not important in the study. Firstly, it is assumed that the effect of the higher uncorrelated "fake hit" density in a muon collider can be minimized in a well designed vertex detector using the redundancy afforded by the several vertexing layers. Secondly, the Higgs factory muon collider will have a beam spot size in the hundreds of microns which, in contrast to the smaller spot at a linear collider, will give little useful vertex constraint to assist the vertexing algorithm. The lack of a vertex constraint is important today's collider detectors that use 2-D vertexing with silicon microstrips and only 2 or 3 layers of vertexing e.g. the LEP and Tevatron detectors. For these geometries the additional constraint would be very helpful. However, it is probably reasonable to assume that the loss would be much less in a multi-layer 3-D pixel vertex detector such as one would expect in a future muon collider.

The purity vs. efficiency curves from the DESY study are shown in figure 2.2.2 of the DESY CDR [2]. All of the curves have a fairly flat purity out to a certain efficiency then dive quite steeply, so little is lost in either purity or efficiency by choosing the efficiency and purity values at this lip of the curve. These values for 1.0 and 2.2 cm inner radii and b- and c-tagging are given in table 1. The table also gives the assumed extrapolation to the 5.0 cm radius at a muon collider.

The extrapolated values were estimated by noting that the extrapolation ratio 2.2:5.0 cm is similar to the ratio between the 2 DESY values, 1.0:2.2 cm. The extrapolation to the muon collider scenario is rather modest since the observed changes between 1.0 cm and 2.2 cm are relatively small. Thus, it is considered that this specific choice of extrapolation introduces little uncertainty and should be entirely adequate for estimates of the physics potential of the Higgs factory muon collider – certainly until a detailed detector design and simulation is arrived at.

The purities in table 1 refer to an equal mixture of c and b jets. For dealing with an arbitrary mixture of b and c jets it is useful to convert these purities into efficiencies for tagging the wrong type of jet. For an equal sample of b's and c's and subscript i (j) denoting the intended (wrong) tag it is clear that:

$$p_i = \frac{e_i}{e_i + e_j}, \quad (1)$$

TABLE 1. Jet tagging efficiencies and purities for an equal sample of b and c jets in the central region of the vertex detector. The values for 1.0 cm and 2.2 cm were read off from the curves for APS's in figure 2.2.2 of the DESY CDR and these values have been extrapolated to give efficiencies and purities at 5.0 cm.

tag	radius	efficiency (e)	purity (p)
b-tag	1.0 cm	63 %	97 %
b-tag	2.2 cm	59 %	97 %
b-tag	5.0 cm	55 %	97 %
c-tag	1.0 cm	46 %	74 %
c-tag	2.2 cm	42 %	71 %
c-tag	5.0 cm	38 %	68 %

so solving for e_j gives:

$$e_j = e_i \times \left(\frac{1}{p_i} - 1 \right) \quad (2)$$

This gives the jet tagging efficiencies of table 2 for the central region of the detector.

TABLE 2. Jet tagging efficiencies for b- and c-tagging in the central region of the vertex detector for a Higgs factory muon collider. The innermost tracking layer of the vertex detector is assumed to be at 5.0 cm from the ip.

tag	eff. for b jets	eff. for c jets
b-tag	55 %	2 %
c-tag	18 %	38 %

C Event Tagging Efficiencies

The jet tagging efficiency must be converted to an event tagging efficiency. Each Higgs decay to $b\bar{b}$ or $c\bar{c}$ will produce an event with two approximately back-to-back jets with the same quark flavor. In this subsection, the event tagging efficiency and rejection factor against wrong flavor events is calculated from the assumed jet tagging efficiencies using a simple algorithm for combining the jet tagging information from the two jets. Several simplifying approximations are used.

Since the jets are fairly back-to-back it will be assumed that either both jets are central or neither jet is. Therefore, the calculation is done assuming central events and then the efficiency is multiplied by an overall geometrical acceptance factor of $\cos(\pi/4) = 1/\sqrt{2}$. Since the Higgs decay is isotropic this is roughly equivalent to assuming that jets more than 45 degrees from the beam direction can be considered central enough for reliable vertex tagging.

TABLE 3. Probabilities for tagging 0,1 or 2 jets if the jet tagging efficiency is e .

number of tagged jets	probability
0	$(1 - e)^2$
1	$2e(1 - e)$
2	e^2

The simple event tagging strategy is to require either one or both of the 2 jets to be tagged correctly and also to require that neither was tagged as the incorrect flavor. From table 3, it is seen that the probability for the first condition is $1 - (1 - e_i)^2$ and for the second condition is $(1 - e_j)^2$. (As before, i denotes the correct jet tag and j the incorrect tag.) If the simplifying assumption is made that the two probabilities are independent and the $1/\sqrt{2}$ geometrical acceptance is included then the efficiency, E_{ii} , for correctly tagging the event is:

$$E_{ii} = \frac{1}{2} \times [1 - (1 - e_i)^2] \times (1 - e_j)^2. \quad (3)$$

Clearly, the probability, E_{jj} for tagging the wrong event type is obtained by simply swapping the i 's and j 's:

$$E_{jj} = \frac{1}{2} \times [1 - (1 - e_j)^2] \times (1 - e_i)^2, \quad (4)$$

and the rejection factor R against the wrong flavor event is defined naturally to be

$$R = \frac{E_{ii}}{E_{jj}}. \quad (5)$$

The $b\bar{b}$ and $c\bar{c}$ tagging efficiencies and rejection factor against the wrong flavor are given in table 4.

II TAU EVENT TAGGING

The tagging of $h \rightarrow \tau\bar{\tau}$ events appears to be much easier than the tagging of quark jets. An s-channel Higgs factory will produce Higgs at rest and

TABLE 4. Event tagging efficiencies and wrong-flavor rejection factors for $b\bar{b}$ and $c\bar{c}$ events at a Higgs factory muon collider. A geometrical acceptance factor of $1/\sqrt{2}$ is included in the efficiencies.

event type	efficiency, E_{ii}	rejection factor, R
$b\bar{b}$	54 %	50
$c\bar{c}$	42 %	8

not in association with other particles, so the geometry should be identical to the $Z \rightarrow \tau\bar{\tau}$ events seen in the LEP and SLD detectors operating at the Z pole energy. These distinctive events consist of almost back-to-back high energy tracks emanating from the ip. Each side is usually a single track – i.e. a “1-prong”, with an 85.5 % probability per side – with almost all of the remainder being tightly collimated “3-prong” jets. The tau lifetime is long enough ($c\tau = 88$ microns) that the slight offset of the prongs from the ip should be observable in a precise vertex detector, but vertexing information should not generally be required to identify this event sample. Therefore, the purity of the sample should be close to 100 % and the efficiency should be dominated by the geometrical acceptance of the central tracker. For all practical purposes, physics studies could reasonably assume a purity of 100% and a conservative efficiency of $\cos(\pi/4) = 0.71$.

III CONCLUSIONS

Heuristic estimates have been made of tagging efficiencies and purities in an s-channel muon collider Higgs factory for the 3 main decay modes of a light Higgs boson. The estimates for the $b\bar{b}$ and $c\bar{c}$ modes are given in table 4, while the $\tau\bar{\tau}$ mode is assumed to have approximately a 71 percent efficiency with essentially 100 percent purity.

REFERENCES

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